# Cross-Layer Adaptive Routing and Wavelength Assignment in All-Optical Networks

Yvan Pointurier, Maïté Brandt-Pearce, Suresh Subramaniam and Bo Xu

***Abstract*—In WDM all-optical networks where electrical regeneration is not available, physical impairments due to propagation in the fibers, amplifier noise, and leaks between channels and in the switches cannot be removed at the physical layer. These effects cause calls, especially between physically distant nodes, to be rejected because they cannot meet minimum Quality of Transmission (QoT) requirements, as measured by signal bit-error rates. It is possible to mitigate physical layer effects at the network layer using appropriate Routing and Wavelength Assignment (RWA) algorithms. We present new RWA algorithms which account for physical impairments in their design and increase QoT and fairness among users without sacrificing low blocking probabilities in metropolitan-sized networks. We also present RWA algorithms that can sharply decrease blocking probabilities in regional-sized networks using optional channel coding. All algorithms are evaluated through simulation in realistic scenarios and shown to successfully mitigate crosstalk effects and to perform better in terms of QoT and network access fairness than traditional algorithms.**

***Index Terms*—Crosstalk, nonlinearities, routing and wavelength assignment, transparent optical networks, wavelength division multiplexing.**

## I. INTRODUCTION

In current, so-called opaque, optical networks, signals are regenerated at the nodes by electronic devices. As optical technology evolves and datarates increase (40 Gbps per channel over tens of channels per fiber is now a reality), electronic nodes become bottlenecks. In transparent, *all-optical* networks, the electronic nodes are replaced with all-optical crossconnects (OXCs) where signals are switched entirely in the optical domain thereby removing completely the current electronic bottlenecks. By their design, all-optical networks allow for signals to propagate over very long distances, potentially thousands of kilometers, with no regeneration[1]. In this paper, we use cross-layer techniques to reduce the impact on network operation and fairness to the users of the physical impairments that signals sustain while travelling over very long physical distances, .

A key feature of optical networks is their capability to deliver data with low bit-error rates (BER) over long distances. However, as transmission distances increase, signals are subject to more severe physical impairments: inter-symbol interference (ISI) appears because of the fiber chromatic dispersion, nonlinear effects (Self Phase Modulation, SPM), and polarization mode dispersion (PMD); noise that is generated in optical amplifiers accumulates; and nonlinear interchannel interference, or *nonlinear crosstalk*, appears in WDM and more particularly in dense WDM (DWDM) systems due to fiber nonlinear effects (cross-phase modulation, XPM, and four wave mixing, FWM) [4]. These effects affect traditional optical networks and are enhanced by the propagation distances involved in all-optical networks. In addition, optical signal leaks that occur in the OXCs, either at the demultiplexing stage due to imperfect filtering or inside the switching fabric, co-propagate with legitimate signals over possibly very long distances. These leaks, called *node crosstalk*, accumulate as nodes are being traversed [5] and can be enhanced by the fiber characteristics as propagation distances increase [6]. Therefore, all-optical networks are subject to physical impairments that are static and depend on the network topology only, such as ISI and noise, but also other physical impairments that are dynamic and can vary with the network state, such as nonlinear and node crosstalks. As a result, Quality of transmission (QoT) of signals in a network, as measured by their BER, is also dependent on the network state.

Much research has been carried out in the past decades to reduce physical impairments at the physical layer, leading for instance to the development of low-noise amplifiers and the design of complex dispersion maps or dispersion compensation devices; however, residual degradation still remains, and crosstalk for instance cannot be filtered out at the physical layer since leaked signal and legitimate signal share the same spectral band. Routing and Wavelength Assignment (RWA) has emerged as a method to mitigate physical impairments in all-optical networks at the network layer. Since wavelength conversion is not yet mature for commercial deployment, a call in an all-optical network must use the same wavelength from source to destination, a constraint known as the *wavelength continuity constraint*. The role of RWA algorithms is to assign a route and a wavelength — the combination of which is called a *lightpath* — to incoming calls in a network, in order to satisfy an optimization goal, such as the minimization of the average call blocking probability in the network [7]. However, since QoT in all-optical networks depends on the network state, not only must RWA algorithms find a lightpath that meets the wavelength continuity constraint, but also the selected lightpath must meet the *QoT constraint*; in this work,

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Parts of this paper have been presented at IEEE OFC’2006 [1], IEEE ICC’2006 [2], and IASTED OCSN’2006 [3].

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This work was partly supported by the National Science Foundation (NSF) under grants CNS-0520060 and CNS-0519911.

[1] Although all-optical regeneration is currently the focus of much research, it is not yet commercially available.

a QoT constraint is a fixed BER threshold that each lightpath cannot exceed at any time. In addition to minimizing blocking probability, it is desirable for RWA algorithms to exhibit high QoT (i.e., low average call BER) instead of only ensuring that each call satisfies a minimum level of QoT. Indeed, operating a network far from the BER threshold permits more flexibility in the network. It improves the network scalability, as adding links or nodes, and therefore increasing the amount of crosstalk injected in the network, moves the BER of lightpaths closer to, rather than across, the BER threshold. Similarly, operating with a BER margin mitigates the effects of hardware aging, and finally lower BERs can help increase the actual data throughput in the network by limiting the number of retransmissions at higher layers, such as TCP for instance.

In this paper, we present four new RWA algorithms (SP2, HQ, MmQ, MmQ2) that belong to the class of *adaptive* RWA algorithms [8], which are known to perform well in terms of blocking probabilities. The new RWA algorithms are QoT-aware in the sense that they ensure (during admission control) that all lightpaths in the network meet a QoT (BER) constraint without disrupting previously established lightpaths, and that they explicitly account for QoT when determining which lightpath a call should use. Furthermore, SP2 and MmQ2 implement the so-called *protecting threshold* technique described in [9] where short lightpaths are not established when free wavelengths are sparse, to keep more resources for longer lightpaths and hence enhancing fairness in the network. We give the time complexity of our algorithms; although our algorithms are complex, they run in polynomial time and can be used in applications where circuits are established for moderate (seconds, minutes) to extended (hours and more) periods of time, such as in e-science collaboration [10]; they are not, however, suitable for very short-lived circuits establishment as is done in Optical Burst Switched networks [11]. Although analytical techniques for evaluation of QoT-aware RWA algorithms have been proposed recently [12], they are not yet applicable to adaptive algorithms and thus we rely on extensive simulations to evaluate our algorithms. We evaluate our new QoT-aware algorithms against the traditional SP (Shortest Path) algorithm on two realistic large metropolitan-sized networks and show gains in performance in terms of average call BER and fairness, without sacrificing low blocking probability.

The RWA problem has been given attention recently for problems involving QoT-awareness; for instance, one or more of the following impairments: noise, PMD, Four Wave Mixing, residual dispersion and average nonlinear phase variation, and electrical regeneration cost, have already been included in various RWA algorithms [13]–[19]. These works overlook node crosstalk. The algorithms presented in [20]–[22] incorporate many impairments, including node crosstalk, at the admission control step only. In addition, [22] deals with the case of translucent networks, where some nodes can regenerate signals electronically; our work considers transparent networks where the only regeneration mechanism available at the nodes is optical amplification. Similarly, [23] focuses on call admission control; a RWA formulation is proposed, but it requires a computationally expensive linear optimization step, in addition to physical impairments computations. Our algorithms are less computationally intensive. We proposed in the past RWA algorithms that incorporate node crosstalk both at the admission control and at the route selection step [24] or wavelength assignment step [25]. These algorithms were based on fixed alternate routing algorithms where routes are chosen among a predefined set of candidates (alternates). This paper presents an adaptive routing scheme where routes are computed given the current network state. In [26], an adaptive routing scheme accounting for physical impairments is presented. Despite using a similar approach, [26] and our work differ in three fundamental respects. First, we account for node crosstalk; second, the technique presented in [26] relies on an iterative heuristic to solve an integer program, and it is not clear how complex the heuristic is (although the authors do claim that the heuristic always converges): our technique runs in a guaranteed polynomial time with all variables and appears to be less computationally intensive; third, we propose several wavelength assignment schemes that are not investigated in [26], and which we show lead to desirable properties such as fairness, which is introduced next.

In addition to QoT-awareness, another desirable property for RWA algorithms is *fairness*. Fairness was defined and quantified by a *fairness index*, a number between 0 and 1, in the general context of circuit-switched networks in [27] and refers to how resources are shared between users: a fairness index of 1 means that resources are equally shared between users while a low fairness index indicates that some users enjoy access to the resources when others do not. Fairness in the context of RWA has received little attention. Birman and Kershenbaum presented techniques to improve blocking probability fairness in [9]. These techniques were assessed graphically rather than with a metric in the context of alternate routing in [28]. In [29], blocking probability fairness is evaluated in translucent networks, but not for transparent networks.

The algorithms discussed above are able to mitigate crosstalk effects. However, in the case of large networks where some node pairs have no viable paths satisfying QoT even with just ISI and accumulated noise, none of the algorithms discussed above is able to establish lightpaths for these pairs. This leads to high blocking probability and low fairness. In [30], we proposed a new class of RWA algorithms to address this issue. These algorithms implement optional coding: they try to establish several lightpaths for calls that would otherwise violate the QoT constraint; coding is used on each of these lightpaths. In this paper, we evaluate RWA with optional coding in scenarios with crosstalk impairments in addition to ISI and noise, measuring blocking probability, BER and fairness. We show using simulations over a regional-sized network that our algorithms with optional coding decrease average call blocking probability, reduce crosstalk impact on call blocking probability, decrease average BER and improve fairness compared with the similar RWA algorithm with no optional coding capability.

This paper is organized as follows: in Section II, we present the assumptions concerning the physical layer and network modelling we use throughout this work. In Section III, we present fair QoT-aware adaptive RWA algorithms and evaluate them through simulation on a large metropolitan-sized network. In Section IV, we present a QoT-aware adaptive RWA algorithm with optional coding, which we evaluate through simulation. We draw brief conclusions in Section V.

## II. ASSUMPTIONS AND SYSTEM DESCRIPTION

We now state our assumptions concerning the modelled network. We consider a network of bidirectional links with $C$ equally spaced wavelengths in each direction. Although all-optical wavelength conversion is the subject of much current research, the technology is not yet mature for deployment in the near future and thus we assume that wavelength conversion is not available. Calls are assumed to arrive in the network according to a Poisson process with average arrival rate $\ell$ and the calls durations are assumed to follow an exponential distribution with unit mean, such that $\ell$ is the *total offered load* of the network in Erlang. Call sources and destinations are uniformly distributed over the set of network nodes.

We assume the existence of a *centralized* Network Management System to perform call admission control, Routing and Wavelength Assignment, call establishment and termination. Typically, a low-speed control channel, which is not modelled here, is reserved to manage the network. When a call is accepted in the network, it is assigned one (Section III) or potentially several (Section IV) *lightpaths*; a lightpath is the combination of a wavelength and a sequence of nodes and links called *route* or *path*. Physically, the links consist of one or several *spans*; each span in turn consists of single mode fiber, an amplifier that compensates for the fiber linear attenuation, and a dispersion compensation (DC) device that compensates for the fiber chromatic dispersion. The receiver is modeled by an optical filter (for demultiplexing purposes), followed by a photodetector per channel (a square-law device, a time sampler and a narrow electrical filter). A sample lightpath is shown in Fig. 1.

Because of the physical impairments sustained by signals during their transmission on a lightpath, a signal may be too degraded at reception to ensure a minimal QoT as defined by the network administrator. Traditionally, QoT for a signal is measured by its BER, which should not drop below a predefined threshold. We assume on-off keying signaling and, denoting by $\mu_1$ and $\mu_0$ the means of the received “1” and “0” samples and by $\sigma_1$ and $\sigma_0$ their respective standard deviations, the *Q factor* of a signal is defined as:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1}. \tag{1}$$

Using a Gaussian assumption [31], the BER and the Q factor of a signal are related by $BER = 0.5\mathrm{erfc}\big(Q/\sqrt{2}\big)$ for uncoded signals. For instance, a BER of $10^{-9}$ corresponds to a Q factor of $Q = 6$.

In this work, we account for four of the main physical impairments which are known to affect lightpaths in all-optical networks [32]: intersymbol interference, amplifier noise, nonlinear crosstalk, and node crosstalk. Each of these effects is accounted for as a noise variance in the Q factor of the lightpath, that is, for a given lightpath:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sigma_{nlx}^2 + \sigma_{nx}^2}} \tag{2}$$

where $\sigma_i^2$, $\sigma_n^2$, $\sigma_{nlx}^2$ and $\sigma_{nx}^2$ are the variance contributions due to intersymbol interference, amplifier noise, nonlinear crosstalk and node crosstalk, respectively. (Crosstalk and amplifier noise contributions to $\sigma_0$ are higher order terms which can be safely ignored, hence $\sigma_0$ is only an ISI term here.) In this paper, we ignore PMD effects; PMD effects should be included for very high datarate networks (40 Gbps) and could be included in our RWA algorithms as a maximal lightpath length to be enforced.

First, ISI is a single-channel effect that results from chromatic dispersion, SPM, and filtering at the receiver; ISI depends only on the lightpath topology: span lengths, amplifier and dispersion compensation devices placement, fiber and receiver physical characteristics; ISI is independent of the network state.

Second, amplifier noise is injected by each amplifier on the path and is due to the so-called Amplifier Spontaneous Emission (ASE) phenomenon. Amplifier noise also depends on the lightpath topology only, and is independent of the network state. We assume an Amplifier Gain Control (AGC) EDFA model operated at input power levels below saturation. Both ISI and ASE effects can be predetermined given a network topology and physical characteristics of the network building blocks.

Third, nonlinear crosstalk occurs when two (in the case of XPM) or three or four (in the case of FWM) signals propagate on different channels in the same fiber span. Signal co-propagation in optical fiber results in energy transfers between the signals resulting in impairments similar to noise. These nonlinear effects are stronger when the participating signals are on closer channels and when channel separation is tighter as is the case with DWDM systems [33]. Since nonlinear crosstalk is due to the interaction between several signals in the network, it is a network status-dependent impairment that cannot be precomputed. It is possible to compute $\sigma_{nlx}$ accounting for all nonlinear crosstalk components on a lightpath by summing the variance contributions for each nonlinear crosstalk:

$$\sigma_{nlx}^2 = \sum_p \sigma_{nlx_p}^2, \tag{3}$$

where the sum is taken over all nonlinear interchannel interferences between any existing lightpath in the network and the considered lightpath. In this paper, the variance due to nonlinearity is calculated based on [34]. This method assumes a non-depleting model for crosstalk.

Fourth, node crosstalk originates from signal leaks in the OXCs, either at the demultiplexing stage (port crosstalk) or inside the switching fabric (fabric crosstalk). A lightpath that traverses an OXC actually traverses three stages within the node. First, the wavelengths on each input fiber are *demultiplexed* at the input ports; then, each lightpath is switched spatially by a *switching fabric*; last, wavelengths bound to the same output port are *multiplexed*. More details about node and crosstalk modelling can be found in [25], [35].

Port crosstalk is due to imperfect filtering in demultiplexers and results in channel interference that is in-band to the channel of interest. Adjacent port crosstalk, where channels are adjacent, is stronger than non-adjacent port channel crosstalk. The power of adjacent port crosstalk (as measured by the power attenuation with respect to the launched signal power) can be as high as $-20$ dB. Fabric crosstalk depends only on the technology chosen to build the OXCs and can be as small as $-60$ dB in MEMS fabrics and as high as $-20$ dB in Fiber Bragg Grating fabrics [36]. As with nonlinear crosstalk, node crosstalk is a dynamic effect that depends on the network status. It is possible to compute $\sigma_{nx}$ accounting for all node crosstalk components on a lightpath by summing the variance contributions for each node crosstalk:

$$\sigma_{nx}^2 = \sum_q \sigma_{nx_q}^2, \tag{4}$$

where the sum is taken over all node crosstalk signals between any existing lightpath in the network and the considered lightpath.

The aforementioned physical effects all contribute to increase the blocking probability and average BER in all-optical networks. However, as mentioned in Section I, high fairness, in addition to low BER averages, is desirable. Indeed, in all-optical networks, calls between nodes that are physically distant are blocked more often than calls between closer nodes because both wavelength continuity and QoT constraints are harder to fulfill for longer lightpaths. Similarly, the BER for calls between physically distant nodes is higher than for calls between close nodes. In this paper, we consider two types of fairness, one applied to blocking probability, the other to BER. We design RWA algorithms which are more fair than traditional RWA algorithms in terms of blocking probability and in terms of BER. Fairness in terms of BER is important because, in the context of networks that implement Forward Error Correction (FEC) techniques — difficult to perform at high bitrates, — FEC could be reserved for only those paths that exhibit high BER. With RWA algorithms that are fair in terms of BER and which yield low BERs, FEC can be used on fewer paths and the BER threshold can be relaxed. In this work, we use the definition of fairness introduced by Jain in [27] for circuit-switched networks but applicable to more general situations. The *fairness index* for a resource $X$ shared between $n$ users is a number between $0$ and $1$ that measures how fairly a resource is shared; a fairness index of $1/n$ indicates that a single user utilizes all of the resource while a fairness index of $1$ indicates that all users utilize the resource equally. The formal definition for the fairness index $f_X$ is:

$$f_X = \frac{\left(\sum\limits_{k=1}^{n} X_k\right)^2}{\sum\limits_{k=1}^{n} X_k^2} \tag{5}$$

where $X_k$ is the amount of resource received by user $k$. In this work, the users are pairs of nodes and the resource can be either blocking probability or BER. In the following section, we provide RWA algorithms that exhibit low blocking probabilities, lower BER, higher blocking probability fairness and higher BER fairness compared with traditional RWA algorithms.

## III. FAIR QOT-AWARE ADAPTIVE RWA

### A. Algorithms description

In this section we present five RWA algorithms (SP, SP2, HQ, MmQ, MmQ2) which belong to the class of adaptive RWA algorithms as defined in [8] and provide various degrees of fairness and QoT enhancements. Four of these algorithms are new (SP2, MmQ, MmQ2, HQ) and are compared with a traditional algorithm (SP).

In adaptive RWA algorithms, blocking due to the wavelength continuity constraint is reduced as follows. On a call arrival, a wavelength $\lambda$ in the set of the $C$ wavelengths in the network is selected according to a predefined order and a network topology that contains only links that are not in use by $\lambda$ is determined. A route $R$ is then tentatively selected using a shortest path algorithm on this new topology. If such a path exists then the call is accommodated on lightpath ($R$, $\lambda$). If such a path does not exist then the wavelength continuity condition is not fulfillable on this wavelength and the next available wavelength is chosen.

The standard *exhaustive adaptive RWA algorithm* is an adaptive RWA algorithm where, instead of considering wavelengths in a predefined order and picking the first wavelength for which a route can be found, all wavelengths are considered, hereby yielding at most $C$ possible routes which satisfy the wavelength continuity constraint. A lightpath is established on the shortest of these routes. This standard exhaustive adaptive RWA algorithm yields low blocking probabilities but implements no QoT-awareness or fairness enhancement.

To enhance fairness in some of our algorithms, we use the technique called *protecting threshold* presented in [9]. The protecting threshold technique safeguards from the fact that longer paths are subject to more frequent blocking than shorter paths because of the wavelength continuity constraint. Protecting threshold is even more relevant in the context of crosstalk-impaired networks, because longer paths are subject to higher QoT degradation due to crosstalk; here, wavelength continuity and QoT constraints are both harder to fulfill for longer paths. Protecting threshold facilitates establishment of longer paths by allowing a short lightpath to be established only when the number of wavelengths that are available on the tentative paths is above a preset threshold, hereby saving resources for longer lightpaths. The drawback of protecting threshold is that calls on short paths can be blocked even if wavelengths are available and the technique can therefore be detrimental to the average blocking probability on the network. In this work, we implement the protecting threshold as follows: a single-hop lightpath is blocked if it would use the last wavelength available on the (unique) link that constitutes the lightpath. This corresponds to a threshold (or reservation parameter) of 2 in [9].

We provide a description of our QoT-aware adaptive RWA algorithms in Alg. 1. The first modification to the standard exhaustive adaptive RWA algorithm we propose concerns QoT-awareness; in this work we consider that the QoT constraint is satisfied when the Q factor of all calls in the network is above a predefined threshold $Q_{th}$ which corresponds to operation below a fixed minimum BER. When a lightpath is tentatively established in the network, it is therefore necessary to check that its Q factor is above the preset threshold, but this is not sufficient. Indeed, when a new lightpath is established, it injects crosstalk on all previously established lightpaths with which it shares links (nonlinear crosstalk) or nodes (node crosstalk) and therefore Q factors for those lightpaths have to be checked as well as the Q factor of the tentative lightpath. Lightpaths that share no link nor node with the tentative lightpath are not affected by the insertion of the tentative lightpath and therefore their Q factors do not need to be recomputed. Our algorithms enforce satisfaction of the QoT constraint by computing the Q factors of the tentative lightpath and of all lightpaths that share at least a link or node with the tentative lightpath (see Alg. 1, line 4), and by rejecting the tentative lightpath from the list of candidate lightpaths if any of these Q factors is below the preset threshold.

The second modification lies in the selection of the route among the list of (at most $C$) candidates and concerns both QoT awareness and fairness enhancement. We propose the following five policies to select the route on which an incoming call is to be accommodated (see Alg. 1, line 11):

- **SP** (shortest path) selects the wavelength that corresponds to the physically shortest path among the candidates [8]; this policy is used as a reference against which other policies are evaluated;
- **SP2** is the traditional shortest path algorithm with protecting threshold and reservation parameter set to 2; this new policy is designed to enhance blocking probability fairness;
- **HQ** (highest Q factor) selects the candidate lightpath with the highest Q factor. This new policy is designed to decrease the average BER in the network.
- **MmQ** (max-min Q factor) is a new, QoT-aware policy. Assuming a wavelength has been chosen, inserting a lightpath increases crosstalk in the network, possibly bringing the Q factor of a previously established lightpath close to the threshold. Operation close to the Q factor threshold is not desirable as it makes the QoT constraint more difficult to fulfill for future incoming calls. MmQ maximizes the margin of QoT operation in the network by selecting the lightpath that maximizes (over the at most $C$ candidates) the minimum Q factor (over the tentative lightpath itself and all lightpaths previously established in the network that the tentative lightpath crosses). MmQ is QoT aware in the sense that its decision is based on QoT rationales. MmQ is designed to decrease the worst case network BER;
- **MmQ2** is MmQ augmented with the protecting threshold technique. MmQ2 is designed to not only decrease average network BER, but also increase blocking probability fairness and BER fairness;

For each policy, ties are broken by choosing the first lightpath in the list of candidates.

As mentioned above, fairness-enhanced algorithms (SP2, MmQ2) may result in higher blocking probability than the reference algorithm (SP). Similarly, although HQ, MmQ and MmQ2, which are designed with QoT in mind, attempt to lower blocking probability due to the QoT constraint, the path they select is not necessarily the shortest path. Therefore these three algorithms may waste network resources and make wavelength continuity constraint harder to fulfill for future calls. In the next section, we show with simulations that the trade-offs between wavelength continuity and QoT constraints, between lower blocking probability and higher QoT, and between lower blocking probability and higher fairness, do not result in a substantial increase in overall blocking probability.

We note here that it is possible to select $k$ shortest paths instead of the one shortest path in the adaptive routing step, for given source, destination and wavelength, in order to increase the size of the pool of the candidates. However, establishing longer lightpaths than the shortest path would incur an additional waste of resources, as previously highlighted; moreover, longer lightpaths tend to be subject to higher physical impairments, thereby decreasing the probability that it is chosen over a shorter lightpath.

### B. *Complexity analysis*

Consider a network of $V$ nodes and $E$ links, each carrying $C$ wavelengths. We denote by $P$ the maximum number of neighbors (adjacent nodes) of a node in the network and $H$ the maximum length in hops of a lightpath. Alg. 1 computes, for each wavelength $\lambda$, a modified topology where all links where $\lambda$ is used are removed, a shortest path, and the Q factors for all lightpaths that share at least a link or node with the aforementioned shortest path. Since at most $HC$ lightpaths have a link or node in common with a given lightpath, the time complexity of Alg. 1 is $O(C(E + V \log V + HC\mathcal{Q}))$, where $\mathcal{Q}$ is the time complexity of computing a single $Q$ factor for a lightpath.

Our RWA algorithms require online Q factor computations because Q factors cannot be pre-computed as $\sigma_{nlx}$ and $\sigma_{nx}$ depend on the network status. However, it is possible to pre-compute, for all paths: $\mu_1$, $\mu_0$, $\sigma_0$ and $\sigma_i$ using very short simulations [35]; $\sigma_n$ with the fast, analytical method we developed in [37]; $\sigma_{nlx_p}$ for a single nonlinear crosstalk interference $p$ using (3) and the analytical method described in [34]; and $\sigma_{nx_q}$ for a single node crosstalk interference $q$ using (4) and the fast method presented in [35]. Therefore, we can compute $\sigma_{nlx}$ and $\sigma_{nx}$ online using simple summations of values that can be found in pre-computed tables, and thus we can compute Q factors online with (2) using table lookups for $\mu_1$, $\mu_0$, $\sigma_0$, $\sigma_i$, $\sigma_n$ and the aforementioned values for $\sigma_{nlx}$ and $\sigma_{nx}$, the time complexities of which we now derive. The time complexity to compute $\sigma_{nlx}$ is the number of terms in the sum, i.e., the number of interferences between a considered lightpath and other lightpaths. Nonlinear crosstalk on a lightpath is caused, on each fiber span, by the interactions between at most 3 signals and the lightpath itself; thus, there can be at most $HC^3$ such interferences on a given lightpath: the time complexity to compute $\sigma_{nlx}$ is $O(HC^3)$. Similarly, the time complexity to compute $\sigma_{nx}$ is the number of interferences sustained by the considered lightpath. The node crosstalk model identifies in [25] three different kinds of crosstalk sources; it can be shown that their respective time complexities are $O(P)$, $O(C)$, and $O(PC)$. For a lightpath of $H$ hops the time complexity is thus $O(H(C+P+PC))=O(HPC)$, hence the time complexity to compute a single Q factor is $\mathcal{Q}=O(HC(C^2+P))$. Overall, the time complexity for Alg. 1 is $O(C(E+V\log V+H^2C^2(C^2+P)))$. This complexity may seem high, especially with respect to number of wavelengths, however our new algorithms are based on exhaustive adaptive RWA, therefore they have the same complexity as the reference algorithm (SP) and are much less complex than algorithms that search for an optimal solution over the complete set of possible lightpaths, which is an NP-complete problem [7].

### C. Evaluation through simulation

We evaluate our algorithms on the NSF network (NSFNET) and China Education and Research (CERNET) topologies depicted in Figs. 2 and 3, with the physical parameters from Table I. We have computed the maximum distance achievable in either of these networks for a path subject to a varying number of adjacent port crosstalk signals and report the results in Table II. The maximum distance achievable in the downscaled networks while maintaining good QoT ($BER \leq 10^{-9}$) and assuming physical impairments due to ISI and noise only is $12$ spans. (Distances much longer than $12$ spans are achievable using optimized long-haul link design and components, which are not the focus of this work.) Moreover, if as few as $10$ adjacent port crosstalk signals are injected on a lightpath, then the maximum transmission distance on the considered lightpath is only $6$ spans. Because maximum achievable distances are lower than the real distances involved in the original NSFNET and CERNET topologies, the NSFNET (respectively, CERNET) topology we are using for our simulations is scaled down by a factor of $10$ (resp. $4$) with respect to the real NSFNET (resp. CERNET) topology to model large metropolitan networks. We provide the distribution of the lengths of the shortest paths in the downscaled NSFNET topology in Table III. Since all shortest paths between any two nodes are $8$ spans long or less with this topology, even node crosstalk can have disruptive effects in the network in terms of blocking probability due to the QoT constraint. The simulation results shown in Figs. 4–11 are obtained by simulating the routing and wavelength assignment of $20000$ calls. Each data point is obtained by repeating this process $10$ times in order to compute 95% confidence intervals, which are shown on the plots.

In Figs. 4 and 5, we show, for each topology, the blocking probability when all physical impairments are accounted for, for all five RWA algorithms discussed above and different total offered network loads (top panel). The SP algorithm tends to perform best and the MmQ2 worst; however, the differences in average blocking probabilities for all algorithms are small and overall all algorithms perform very similarly. Further investigating the origin of blocking probabilities for one of the algorithms, MmQ2, consider the bottom panels in Figs. 4 and 5. The difference between the topology-related impairments only (ISI and noise) case and the all-effects (ISI, noise, nonlinear and node crosstalk) case is close to one order of magnitude in average blocking probability. Furthermore, we observe that blocking probabilities for cases including only one of the crosstalk effects are similar: impact of nonlinear crosstalk is only slightly higher than that of node crosstalk. Therefore, inclusion of both kinds of crosstalk is important when evaluating RWA algorithms for blocking probability.

The average BER in the network is shown in Figs. 6 and 7 for the various algorithms (top panels). Notice that the curves for SP and SP2 are almost identical, and so are the curves for MmQ and MmQ2. As expected, all three algorithms designed with QoT in mind (MmQ, MmQ2, HQ) perform better than SP and SP2, especially for lower loads. Furthermore, MmQ and MmQ2 perform very close to one another, showing that additionally tuning MmQ for fairness does not harm its performance in terms of BER. The HQ algorithm performs best, yielding BERs at least half lower than those of other algorithms. The BER performance of the network is further investigated (bottom panels of Figs. 6 and 7) for the MmQ2 algorithm: state-dependent physical effects are responsible for an increase of one order of magnitude for the average BER in the network, with both node and nonlinear crosstalk effects increasing BER similarly.

We show how our algorithms perform in terms of fairness in Figs. 8, 9, 10, and 11; fairness indices lies between $0$ and $1$ with higher values being desirable. First, we study blocking probability fairness in Figs. 8 and 9. For the NSFNET topology, the MmQ2 algorithm exhibits the highest fairness even compared to SP2 which was designed to improve fairness, while for the CERNET topology SP2 performs best, with SP, MmQ2 and MmQ slightly less fair. The HQ algorithm performs significantly lower than other algorithms as it is only designed to improve QoT. We observe that fairness for the CERNET topology is generally low; this is because, with our scaling factors, lightpaths are longer in the CERNET topology than in the NSFNET topology and hence the CERNET network operates closer to the physical limits. In particular, in the CERNET topology, the blocking probabilities for some pairs of (physically distant) nodes are high even for low loads, thereby resulting in a high variance in the blocking probabilities among all node pairs and a low fairness, as can be seen from (5).

In Figs. 10 and 11 we study BER fairness; here, the two algorithms designed to provide high margin in terms of BER (MmQ, MmQ2) outperform all other algorithms. Although MmQ2 implements an additional mechanism, the protecting threshold, to improve blocking probability fairness, this mechanism has no impact on the BER fairness property of the algorithm[2].

The study of how the physical layer parameters affect all-optical networks in general is outside the scope of this work; we chose parameters for the crosstalk values that represent typical, “average” values for crosstalk in all-optical networks [38].

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[2] We also evaluated a sixth algorithm, HQ2, which implements the HQ policy augmented with the protecting threshold technique. However, for each of the metrics presented here, HQ2 was outperformed by at least one of the other five algorithms.

Although not studied here, the impact of some technology changes can be forecast. For instance, if filter concatenation effects (ignored here) became important, node crosstalk would decrease through better port isolation, but ISI effects would increase. Moreover, if a wider grid spacing was used, XPM and FWM effects would decrease, and so would node crosstalk since again better port isolation would be easier to achieve. The impact of the variation of some of the crosstalk parameters is studied more in depth in [39]–[42].

In this section, we have shown how different RWA algorithms could improve network performance. With the HQ algorithm, BER is greatly diminished at the expense of fairness compared with other algorithms, while SP2/MmQ/MmQ2 still perform better than the reference algorithm. Fairness, both in terms of blocking probability and BER, is improved with SP2 or MmQ2 (and BER fairness is equivalently improved with MmQ) compared with all other algorithms. These results are obtained without sacrificing average blocking probability as all algorithms perform similarly for this metric.

## IV. QoT-AWARE ADAPTIVE ROUTING AND WAVELENGTH ASSIGNMENT WITH OPTIONAL CODING

### A. *Algorithms description*

In this section, we address a problem that arises when some paths in a network are too long to meet the QoT constraint even in the absence of crosstalk. Indeed, such long paths are always blocked, independently of the network load and some customers are never given an opportunity to communicate with one another. Adding load (and crosstalk) in the network further degrades the performance in terms of blocking probability. In the previous section, with the scaled-down NSFNET topology depicted in Fig. 2, all shortest paths between two nodes are $8$ spans or less, and the Q factor drops below the threshold $Q_{th} = 6$ for paths that are $13$ spans or more, using the physical parameters given in Table I. Therefore, any node is reachable from any other node. Now consider the NSFNET topology from Fig. 2 where the number of spans between any two adjacent nodes is *doubled*, to model a regional-sized network. With this new, enlarged topology, some shortest paths between network nodes are now longer than the maximal achievable distance of $12$ spans[3]. It can be shown that $18$ shortest paths are more than $12$ spans long in the enlarged topology, and hence no algorithm described in the previous section can draw the average network blocking probability below $18/(14 \times 13) \approx 0.1$. The QoT-aware adaptive RWA algorithm presented in this section overcomes this limitation by using optional FEC coding on calls that do not meet the QoT constraint.

FEC coding allows us to trade bandwidth utilization against higher QoT. The principle of our QoT-aware RWA algorithm with optional coding (see Alg. 2) is to use several lightpaths per request for calls that do not meet the QoT constraint. Data on each of these lightpaths is encoded with a FEC code such that the minimal Q factor required for the coded signal to achieve a maximal target BER after decoding is lower compared with the case where no coding is used and where a single lightpath is used for each call. Lightpaths for the same call can use the same route and different wavelengths, or different routes. In this work, we propose to use a simple code, Golay(23,12), for calls that fail to meet the QoT constraint ($Q > Q_{th_1}$ where $Q_{th_1} = 6$ for a target BER of $BER = 10^{-9}$). Since the rate of this code is approximately 1/2, the coded datastream has to use two lightpaths instead of one. The coding gain of Golay(23,12) is $4.4$ dB for $BER = 10^{-9}$ [30]. After coding, the minimum required Q factor can be shown to be reduced to $Q_{th_2} = 3.6$ instead of $6$ for the same BER target of $BER = 10^{-9}$, assuming that a $1$ dB OSNR degradation corresponds to a 1 dB decrease of the Q factor [43]. Our RWA algorithm with optional coding employs coding only for those paths that need it in order to keep the bandwidth (number of lightpaths per call) expansion low. It uses a variation of the QoT-aware adaptive RWA algorithm (Alg. 1) that we described in Section III to find up to two lightpaths per call, and therefore has the same time complexity as Alg. 1.

The QoT-aware adaptive RWA algorithm with optional coding trades bandwidth utilization in the form of the number of lightpaths used per call against looser Q factor requirements. Increasing bandwidth utilization results in higher blocking probabilities due to the wavelength continuity constraint and higher crosstalk imposed upon other lightpaths. Looser requirements on the Q factors decrease blocking probability due to the QoT constraint. Note that none of this was considered in [30]. In the following section, we show that the trade-off actually results in lower blocking probabilities overall on a regional-sized example.

### B. *Evaluation through simulation*

To evaluate the QoT-aware adaptive RWA algorithm with optional coding, we use the NSFNET topology depicted in Fig. 2 where the number of spans between any two nodes has been doubled. The physical parameters for the network can be found in Table I. As discussed in the previous section, about 10% ($18/182$) of the shortest paths in this enlarged topology are too long to be accommodated with sufficient QoT ($BER \leq 10^{-9}$) if no coding is used. Furthermore, the (potentially two) lightpaths used by each call are computed with a slightly modified version of Alg. 1 and the SP policy: instead of exhaustively searching for the shortest path among all wavelengths, wavelengths are picked randomly and Alg. 1 stops as soon as a lightpath is found. This simplification is made to keep simulation times low and does not change the core concept of the QoT-aware adaptive RWA algorithm with optional coding, which is to trade bandwidth against QoT. We evaluate the QoT-aware adaptive RWA with optional coding algorithm against its counterpart where no coding is available and where a call that does not meet the QoT condition is rejected without being given a chance to be assigned two lightpaths instead of one. In all plots (Figs. 12, 13, 14), plain lines refer to algorithms where no coding is available while dashed lines refer to the algorithms where optional coding is available. As in Section III-C, each data point is the result

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[3] A network using new technology could be designed to achieve these distances; the network used simply provides an example of a regional-scaled network using the parameters given.

of the simulation of $10 \times 20000$ calls and 95% confidence intervals are given.

First consider Fig. 12; when no coding is available, blocking probabilities remain above $0.1$ even for the lower load values and when the only impairments are ISI and noise. Node and nonlinear crosstalk have similar impacts on the call blocking probability, with nonlinear crosstalk having a slightly higher impact as already noticed in Section III-C for QoT-aware RWA algorithms with no coding capability. When optional coding is used, and when all physical impairments are accounted for, blocking probabilities are lowered by $0.07$ to $0.1$ — crosstalk effects are almost, but not completely, removed by the utilization of optional coding. Therefore, the trade-off mentioned in the previous section results in an overall blocking probability decrease. In Fig. 13, we show that using coding also contributes in decreasing the average BER (after coding) in the network. Furthermore, coding improves blocking probability fairness as is shown in Fig. 14; for instance, when no coding is available, blocking probability fairness remains between $0.1$ and $0.2$ while it can reach $0.6$ when all effects are accounted for and optional coding is used.

We have shown, using simulation on a large, regional-sized network, how optional coding could reduce blocking probability, improve QoT and improve fairness in networks where some paths are too long to be utilized without coding. Our results (not shown here) indicate that, in networks where all paths are short enough to be utilized without coding, optional coding does not decrease blocking probabilities; in such cases, the bandwidth expansion vs. QoT trade-off results in high blocking probabilities because the shortage of available wavelengths due to the wavelength continuity constraint is not offset by the gains in QoT.

## V. CONCLUSION

We have presented two classes of adaptive QoT-aware Routing and Wavelength Assignment algorithms for networks with physical impairments. When networks are large and heavily loaded, some calls are blocked because chosen lightpaths would experience a poor QoT, as measured by BER. In these cases, our fair QoT-aware adaptive RWA algorithms decrease BER (HQ algorithm) and improve fairness in blocking probability and BER (MmQ, MmQ2 algorithms) without sacrificing low average call blocking probability in the network. These new RWA algorithms account for crosstalk at call admission and path selection steps, and SP2 and MmQ2 additionally implement the so-called protecting threshold technique. In still larger networks, say regional or continental-sized, where some calls would always be blocked even in the absence of crosstalk, the QoT-aware adaptive RWA algorithm with optional coding can establish calls between physically distant nodes using several lightpaths per call and coding over these lightpaths, hereby decreasing call blocking probabilities and achieving lower BER and higher fairness compared to the case where coding is not available. All algorithms are shown to mitigate node and nonlinear crosstalk effects on network operation, both separately and together, using simulations for realistic network scenarios.

Some of our algorithms implement the protecting threshold technique; we used a threshold of 2 wavelengths to determine whether a short (single-hop) or a long (multi-hop) path could be established. Although it is possible to use other values for the threshold and for the distinction between short and long paths, our goal here was to give a proof of concept for the protecting threshold technique applied to QoT-aware adaptive RWA algorithms – fine tuning is left for future work. We notice that some of our results depend on the network topology: for instance, MmQ2 performs best for blocking probability fairness in the NSFNET topology, while SP2 is best for the CERNET topology. Moreover, none of our proposed algorithms is a panacea and outperforms all other algorithms for all studied metric; rather, our study suggests that our algorithms should be evaluated on a case-by-case basis by network operators in order to determine which policy best fits their needs.

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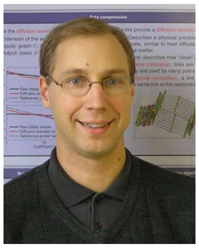

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TABLE I
PHYSICAL PARAMETERS FOR THE SIMULATED NETWORKS.

| **Description** | **Value** |
|---|---|
| Span length | 70 km |
| Signal peak power | 2 mW |
| Bit rate | 10 Gbps |
| Pulse shape | NRZ |
| Fabric crosstalk | $-40$ dB |
| Adj. port crosstalk | $-30$ dB |
| Non adj. port crosstalk | $-60$ dB |
| WDM grid spacing | 25 GHz |
| Fiber loss | 0.22 dB/km |
| Nonlinear coefficient | 2.2 (W km)$^{-1}$ |
| Chromatic dispersion | 17 ps/nm/km |
| Dispersion compensation | 100% post-DC |
| Noise factor | 2 |
| Receiver electrical bandwidth | 7 GHz |
| Number of wavelengths ($C$) | 8 |
| Minimum Q factor:<br>$Q_{th}$, $Q_{th_1}$ (no coding)<br>$Q_{th_2}$ (Golay coding) | <br>6<br>3.6 |

TABLE II
IMPACT OF ADJACENT PORT CROSSTALK ACCUMULATION ON THE MAXIMUM TRANSMISSION DISTANCE.

| **Number of ports contributing to node crosstalk** | 0, 1 | 2, 3 | 4 | 5, 6 | 7, 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|
| **Max. number of spans** | 12 | 11 | 10 | 9 | 8 | 7 | 6 |

TABLE III
LENGTHS OF THE SHORTEST PATHS IN THE NSFNET TOPOLOGY.

| **Length (spans)** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Number of paths** | 20 | 30 | 34 | 36 | 26 | 18 | 14 | 4 |

**Algorithm 1** Generic QoT-aware adaptive RWA
Input: policy, $Q_{th}$.
Output: lightpath $LP$.

```
for i=1 ... C do
    Determine altered network topology considering only links where $\lambda_i$ is free
    Determine the shortest path SP($\lambda_i$) in the altered network topology
    if Q factors for all lightpaths (including the tentative lightpath) are above threshold $Q_{th}$ then
        Mark SP($\lambda_i$) as usable
    end if
end for
if set of usable lightpaths is empty then
    return $LP = \emptyset$ (reject call)
else
    Select a lightpath ("LP") in the set of usable lightpaths according to a predefined policy (SP, SP2, HQ, MmQ, MmQ2)
    return LP (accept call on "LP")
end if
```

**Algorithm 2** QoT-aware adaptive RWA with optional coding.
Input: $Q_{th1}$,$Q_{th2}$.
Output: set $LP$ of up to two lightpaths.

```
Compute $LP$ using Alg. 1 with wavelength random pick (cf. Section IV-B) for the SP policy and $Q_{th} = Q_{th1}$
if $LP \neq \emptyset$ then
    return $LP$ (accept call on $LP$ with no coding)
else
    Compute $LP_1$ using Alg. 1 with wavelength random pick (cf. Section IV-B) for the SP policy and $Q_{th} = Q_{th2}$
    if $LP_1 \neq \emptyset$ then
        Compute $LP_2$ using Alg. 1 with wavelength random pick (cf. Section IV-B) for the SP policy and $Q_{th} = Q_{th2}$
        if $LP_2 \neq \emptyset$ then
            return $LP = LP_1, LP_2$ (accept call on $LP_1$ and $LP_2$ with FEC coding)
        end if
    else
        return $LP = \emptyset$ (reject call)
    end if
end if
```

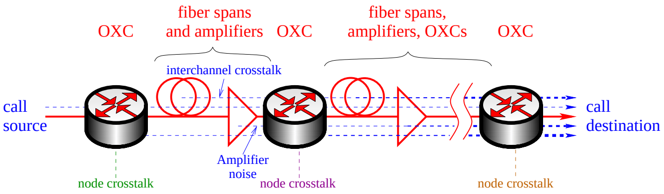

Fig. 1. Model of a transmission lightpath (plain line) used to compute the Q factor. Each OXC can inject one or more node crosstalk components (dashed lines), and nonlinear crosstalk can originate from each span (dotted lines).

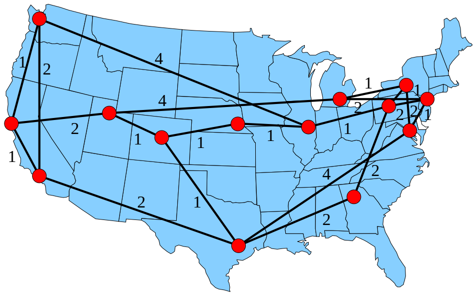

Fig. 2. Down-scaled version of the NSFNET topology (scaling factor: 1/10) used to perform the simulations. On the figure, the weights represent the number of spans for the links.

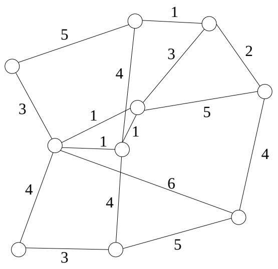

Fig. 3. Down-scaled version of the CERNET topology (scaling factor: 1/4) used to perform the simulations. On the figure, the weights represent the number of spans for the links.

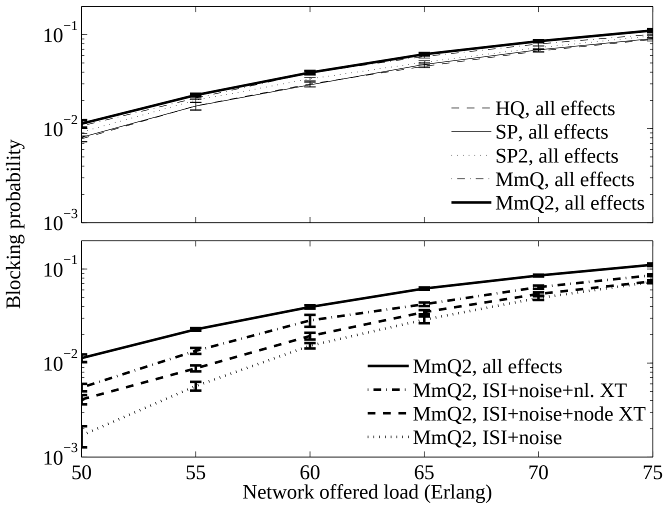

Fig. 4. Call blocking probability for the various QoT-aware RWA algorithms (top panel) and for the MmQ2 algorithm with various physical impairments (bottom panel) [NSFNET topology].

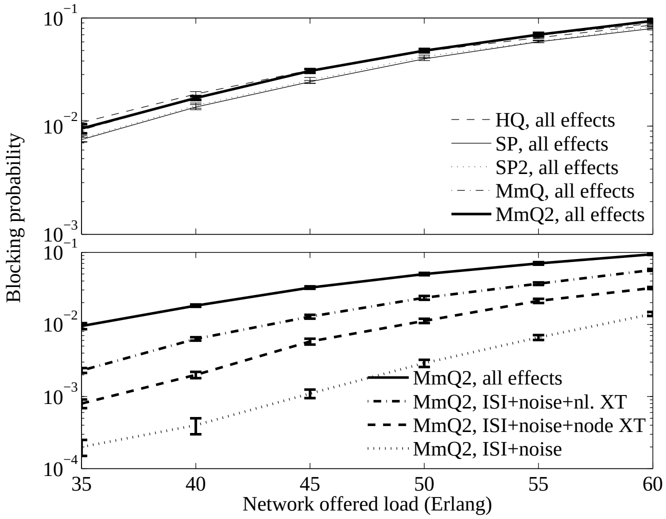

Fig. 5. Call blocking probability for the various QoT-aware RWA algorithms (top panel) and for the MmQ2 algorithm with various physical impairments (bottom panel) [CERNET topology].

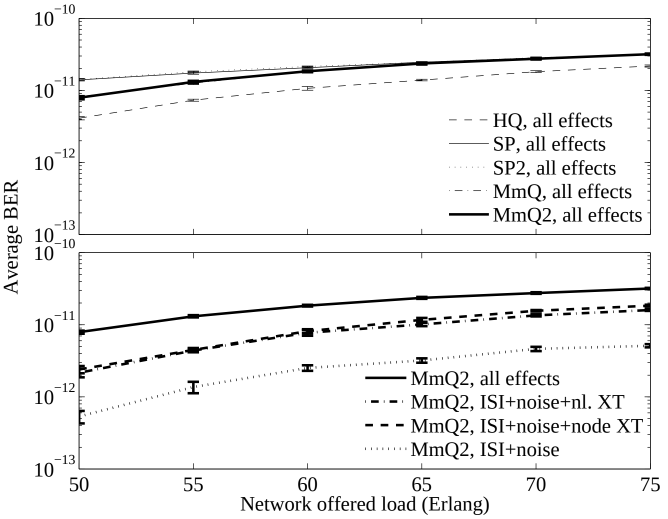

Fig. 6. BER for the various QoT-aware RWA algorithms (top panel) and for the MmQ2 algorithm with various physical impairments (bottom panel) [NSFNET topology].

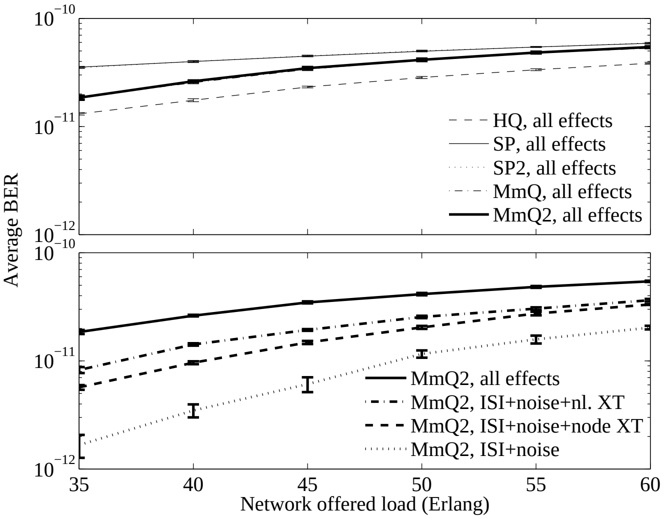

Fig. 7. BER for the various QoT-aware RWA algorithms (top panel) and for the MmQ2 algorithm with various physical impairments (bottom panel) [CERNET topology].

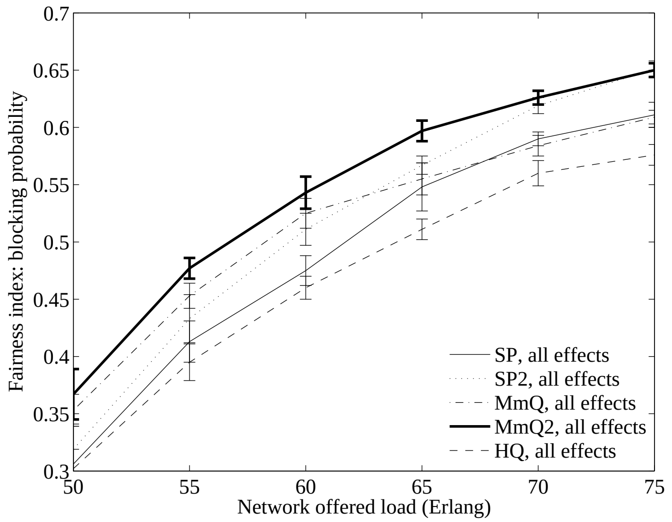

Fig. 8. Call blocking probability fairness for the various QoT-aware RWA algorithms (NSFNET topology).

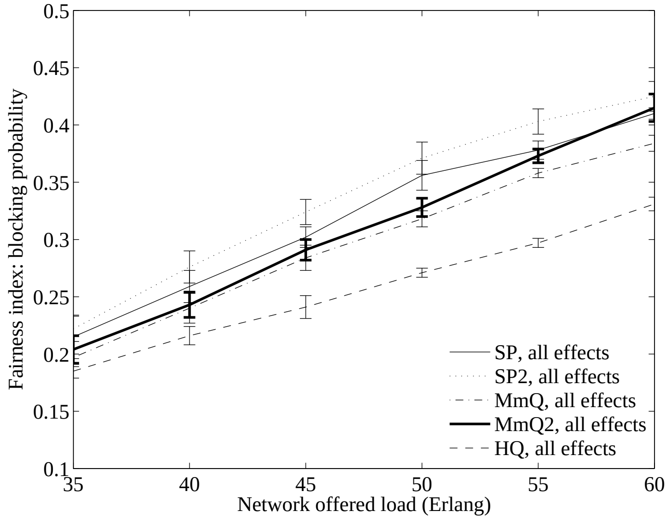

Fig. 9. Call blocking probability fairness for the various QoT-aware RWA algorithms (CERNET topology).

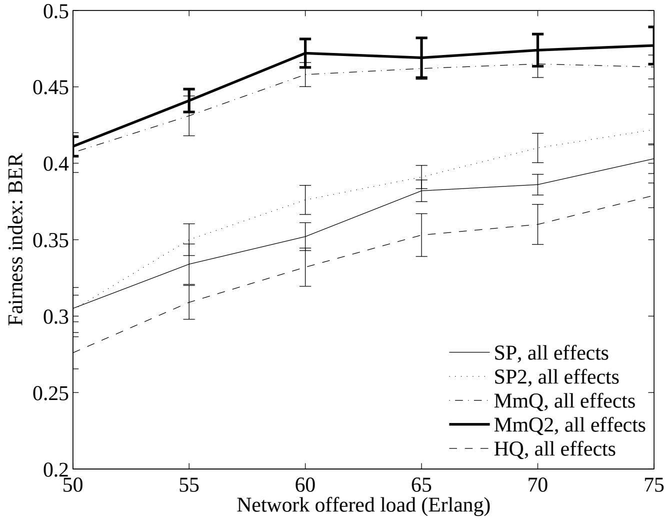

Fig. 10. BER fairness for the various QoT-aware RWA algorithms (NSFNET topology).

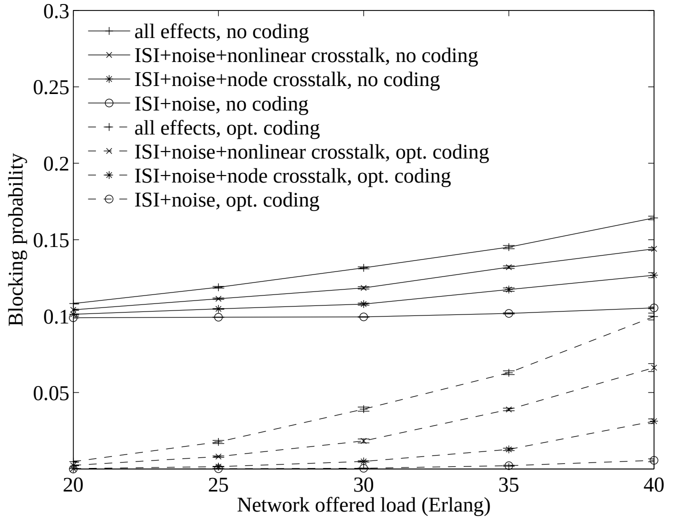

Fig. 12. Call blocking probability for separate physical impairments, for RWA algorithms with and without optional coding (NSFNET topology).

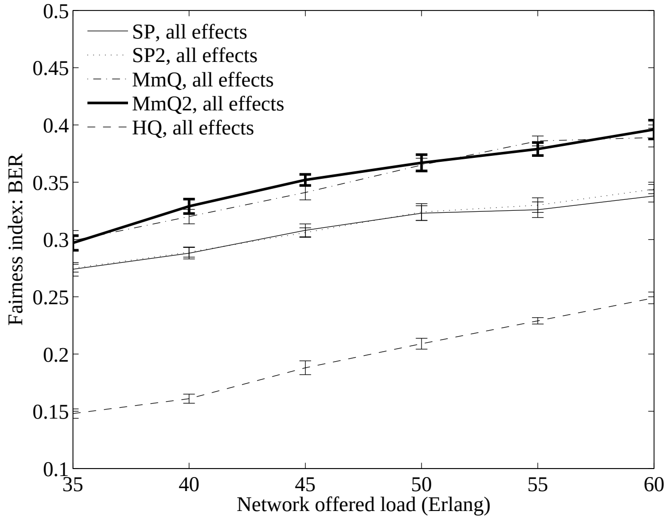

Fig. 11. BER fairness for the various QoT-aware RWA algorithms (CERNET topology).

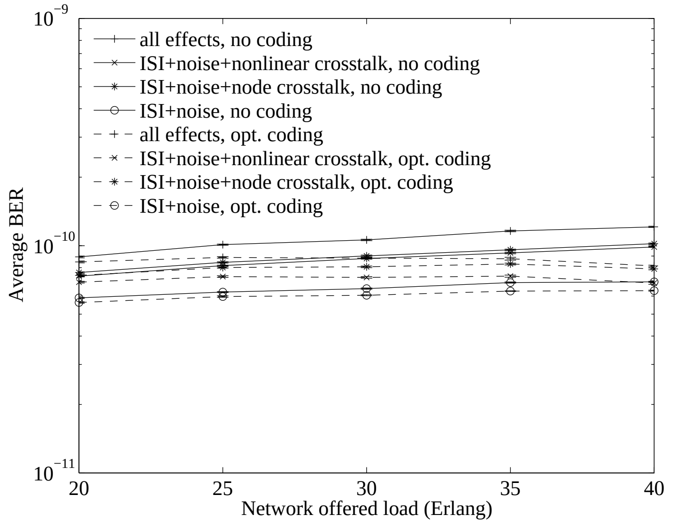

Fig. 13. BER (after decoding) for separate physical impairments, for for RWA algorithms with and without optional coding (NSFNET topology).

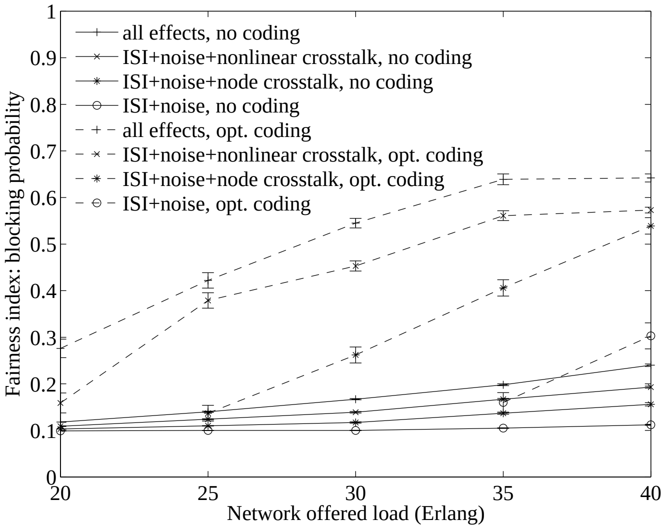

Fig. 14. Call blocking probability fairness for separate physical impairments, for RWA algorithms with and without optional coding (NSFNET topology).